

SHAPES OF DARK MATTER HALOS

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I present an analysis of the density shapes of dark matter halos in Λ CDM and Λ WDM cosmologies. The main results are derived from a statistical sample of galaxy-mass halos drawn from a high resolution Λ CDM N-body simulation. Halo shapes show significant trends with mass and redshift: low-mass halos are rounder than high mass halos, and, for a fixed mass, halos are rounder at low z . Contrary to previous expectations, which were based on cluster-mass halos and non-COBE normalized simulations, Λ CDM galaxy-mass halos at $z = 0$ are not strongly flattened, with short to long axis ratios of $s = 0.70 \pm 0.17$. I go on to study how the shapes of individual halos change when going from a Λ CDM simulation to a simulation with a warm dark matter power spectrum (Λ WDM). Four halos were compared, and, on average, the WDM halos are more spherical than their CDM counterparts ($s \simeq 0.77$ compared to $s \simeq 0.71$). A larger sample of objects will be needed to test whether the trend is significant.

1 Introduction

A variety of observational indicators suggest that galaxies are embedded within massive, extended dark matter halos, lending support to the idea that a hierarchical, cold dark matter (CDM) based cosmology may provide a real description of the universe, especially on large scales (see, e.g., the review by Primack¹¹ and references therein). A useful small-scale test of CDM and variant theories may come from observations aimed at inferring the density structure of dark halos. Specifically, the quest to measure dark halo shapes has developed into a rich and complex subfield of its own.^{4,12}

Predictions for shapes of dark matter halos formed by dissipationless gravitational collapse are most reliably derived using numerical studies.^{6,5,14} These past investigations focused on galaxy-sized halos formed from power-law or pre-COBE CDM power spectra, and found that halos were typically flattened triaxial structures, with short-to-long axis ratios of $s \simeq 0.5 \pm 0.15$. Examinations based on currently favored cosmologies have been done, but they studied only cluster mass halos,^{8,13,9} and also found significantly flattened objects, $s \sim 0.4 - 0.5$. Interestingly, Thomas and collaborators¹³ saw an indication that low matter density models (with early structure formation) tended to produce more spherical clusters than high density models. This result was qualitatively consistent with indications from Warren et al.¹⁴ that high-mass halos are more flattened than (early-forming) low-mass halos. In light of these

hints that formation history plays a role in setting halo shapes, it is important to reexamine the question for a currently standard cosmological model. Specifically, this work aims at characterizing halo flattening as a function of mass and redshift for the popular flat Λ CDM cosmology. I also explore how shapes of halos are affected when going to a Λ WDM model, in which the power spectrum is damped on small scales.

2 Simulations and shape measurement

The simulations were performed using the Adaptive Refinement Tree (ART) code.⁷ The main results are derived from a Λ CDM simulation with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, and $\sigma_8 = 1.0$, which followed 256^3 particles of mass $1.1 \times 10^9 h^{-1} M_\odot$ within a periodic box of comoving length $60 h^{-1} \text{Mpc}$, obtaining a formal force resolution of $1.8 h^{-1} \text{kpc}$. A second simulation was run until $z = 1.8$ with the same particle number, half the box size, and thus eight times the mass resolution; it was used to check resolution issues. Dark halos were identified using a (spherical) bound density maxima method,² and masses were determined by counting particles within the spherical virial radius R_v , inside which the mean overdensity has dropped to a value $\Delta_v \simeq (18\pi^2 + 82p - 39p^2)/(1 + p)$, where $p \equiv \Omega_m(z) - 1$. This sample contains ~ 800 halos that span the mass range $3 \times 10^{11} - 5 \times 10^{14}$.

A second pair of simulations¹ were used to explore how shapes of halos are affected by damping the power spectrum. We compare four halos, each simulated from the same initial conditions, for a Λ CDM and Λ WDM model with the multiple-mass ART code and the same cosmological parameters and effective mass per particle discussed above. The filter mass scale for the Λ WDM run was $1.7 \times 10^{14} h^{-1} M_\odot$, and the four halos we compare have masses $(2 - 8) \times 10^{13} h^{-1} M_\odot$.^a Simulation results were kindly supplied by P. Colín.

Halo axis ratios are determined using the moments of the particle distributions within the virial radius R_v . The short-to-long axis ratio, s , and intermediate-to-long axis ratio q are calculated by iteratively diagonalizing the tensor⁵

$$M_{ij} = \Sigma \frac{x_i x_j}{a^2}, \quad a \equiv \sqrt{x^2 + \frac{y^2}{q^2} + \frac{z^2}{s^2}}, \quad (1)$$

where $q^2 \equiv M_{yy}/M_{xx}$ and $s^2 \equiv M_{zz}/M_{xx}$.

^a Although this filtering mass is much too large to be an consistent with with Ly- α forest measurements,¹⁰ the simulation provides a useful comparison to test the effect of an imposed filtering scale, since the halo masses considered are well within the affected regime. Since

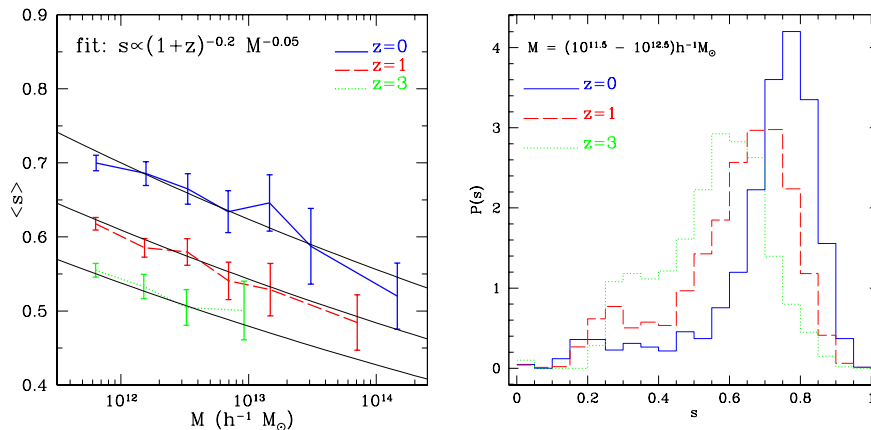


Figure 1: (Left) The average short-to-long axis ratio, s , as a function of halo mass at $z = 0$, 1, and 3. Error bars reflect the Poisson uncertainty associated with the number of halos in each mass bin and *not* the scatter about the relation. (Right) Distribution of measured s values for $\sim 10^{12} h^{-1} M_{\odot}$ halos as a function of z

3 Results

The left panel in Figure 1 shows the average value of s as a function of halo mass for three redshifts, $z = 0$, 1, and 3. Low mass halos, on average, are rounder than high mass halos, as are halos of fixed mass at low z . The relation is well-approximated by $s \simeq 0.7(M/10^{12} h^{-1} M_{\odot})^{-0.05}(1+z)^{-0.2}$ over the mass and redshift ranges explored. The right panel of Figure 1 shows the distribution of s parameters for galaxy-mass halos as a function of z . The average and rms dispersion in these distributions are $s = 0.70 \pm 0.17$, 0.61 ± 0.17 , and 0.55 ± 0.15 , for $z = 0$, 1, and 3, respectively. Note that the distributions are quite non-Gaussian, with a significant tail of highly flattened halos.^b

How do the shapes of halos change with radius? The axial ratios presented in Figure 1 were obtained using particles within R_v . The left panel of Figure 2 shows this average “virial” flattening measurement as a function of halo mass (at $z = 0$) compared with the average s measured within a sphere of radius $30 h^{-1} \text{kpc}$ for each halo. Although the difference is quite small for the low mass halos (since $30 h^{-1} \text{kpc}$ contains much of the halo mass), generally halos

the effect should simply scale with the filtering mass, similar results would be obtained for $\sim 5 \times 10^{10} h^{-1} M_{\odot}$ halos formed from $\sim 1 \text{keV}$ WDM particles.

^b In order to check resolution effects, the $z = 3$ distribution was compared to the corresponding one obtained in the high resolution simulation and found to be statistically equivalent.

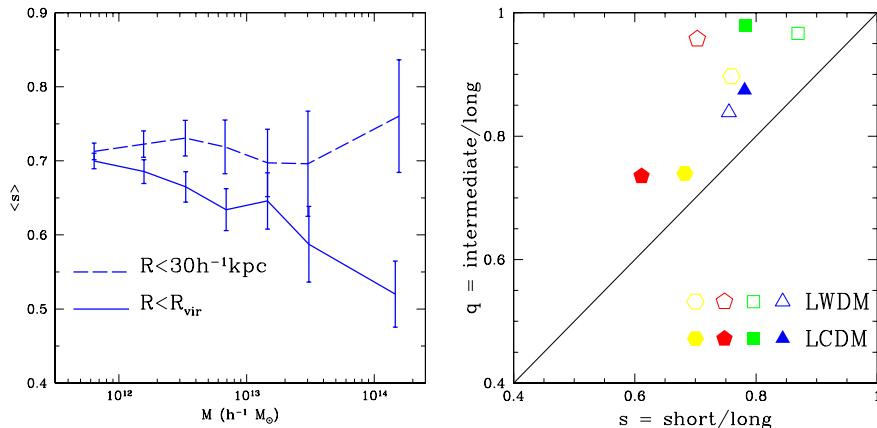


Figure 2: (Left) s as a function of mass measured within halo virial radii R_v (solid) and within $30 h^{-1} \text{kpc}$ spheres from halo centers. (Right) q and s parameters for halos simulated using ΛCDM (solid symbols) and ΛWDM (open symbols) cosmologies. Individual halos, identified by mass and location between the two runs maintain the same symbol shape.

are rounder at small radii. Interestingly, within this fixed central radius, halos typically have the same flattening, $s \sim 0.7$, independent of the halo mass.

Finally in the right panel of Figure 2, we compare the measured s and q values of four halos, simulated in ΛCDM and ΛWDM . There is a tendency for the halos to be rounder (approaching the upper right corner) in WDM, although one halo (designated by the triangles) does become slightly flatter in WDM. The average flattening shifts from $s \simeq 0.71$ for CDM to 0.77 for WDM, but it is difficult to make strong conclusions based on four halos. Indeed, Moore⁹ has simulated a single halo using CDM and WDM power spectra and finds a very similar shape for each. A larger sample of objects will be needed to test for systematic trends.

4 Conclusions

We find that ΛCDM galaxy-mass halos at $z = 0$ are more spherical than previously believed, with $s = 0.70 \pm 0.17$. High mass halos show more substantial flattening, as do halos of fixed mass at high redshift: $s \propto (1+z)^{-0.2} M^{-0.05}$. Halos are also more spherical in their centers, and tend to become more flattened near the virial radius. These trends suggest collapsed structures become more spherical with time, perhaps because they have had more time to phase mix and to obtain isotropic orbit distributions. It is also possible that the

accretion history itself plays a role. Halos formed within a Λ WDM simulation show a slight indication of being less flattened than their Λ CDM counterparts. This may be a reflection of substructure differences between the two models, but a larger number of halos will be needed to decisively test this conclusion. A more complete description of these results, and some discussion of shape correlation with other halo parameters is presented in a forthcoming paper.³

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